

# Baryonium, a common ground for atomic and high energy physics\*

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(Dated: March 12, 2015)

Indications of the existence of quasi-bound states in the  $N\bar{N}$  system are presented. Measurements by BES discovered a broad enhancement close to the  $p\bar{p}$  threshold in the  $S$  wave, isospin 0 state formed in radiative decays of  $J/\psi$ . Another enhancement located about 50 MeV below the threshold was found in mesonic decays of  $J/\psi$ . In terms of the Paris potential model it was shown that these are likely to represent the same state. Antiprotonic atomic data provide some support for this interpretation and indicate the existence of another fairly narrow quasi-bound state in a  $P$  wave.

PACS numbers: 12.39.Pn, 13.20.Gd, 13.60.le, 13.75.Cs, 14.65.Dw

## I. INTRODUCTION

Nucleon-antinucleon quasi-bound states, or states coupled to these, were searched for in the days of LEAR at CERN. Nothing has been found, but broad states or states close to the threshold were not excluded. References [1, 2] indicate conclusions of a long series of measurements. In reference [1] a search for *narrow* signals in the  $\gamma$  spectrum from  $p\bar{p}$  annihilation at rest was performed and no discoveries were found in the region below 1770 MeV and  $\Gamma < 25$  MeV. Experiments looking for missing mass in reaction  $p\bar{p} \rightarrow X\pi$  or  $p\bar{p} \rightarrow Xp$  brought similar conclusions. On the experimental side, one possible reason for the failure is the heavy background due to annihilation processes. Another is the large number of allowed partial waves. On the theory side, it was assumed that the annihilation reaction involve  $\sim 2M_p$  mass transfer and by the uncertainty principle it has to be very short ranged. It was thus expected that widths of quasi-bound states might be narrow. The first part of the argument is still true but it is also known from scattering data that the annihilation potential is strong already at  $p\bar{p}$  separations of  $1fm$ .

TABLE I: Low energy  $p\bar{p}$  states allowed in the  $J/\psi \rightarrow \gamma p\bar{p}$  decays. The first column gives decay modes and specifies the internal states of  $p\bar{p}$  pair. For both photon and  $J/\psi$  the  $J^{PC} = 1^{(-)-}$ . The second column gives  $J^{PC}$  for the  $p\bar{p}$  system.

decay mode	$J^{PC}(p\bar{p})$
$\gamma p\bar{p}(^1S_0)$	$0^{-+}$
$\gamma p\bar{p}(^3P_0)$	$0^{++}$
$\gamma p\bar{p}(^3P_1)$	$1^{++}$

A convincing detection requires selective experiments, and the first such measurement is the decay

$$J/\psi \rightarrow \gamma p\bar{p}, \quad (1)$$

studied by the BES Collaboration [3]. A strong threshold enhancement is observed in the invariant  $p\bar{p}$  mass distribution (see Fig. 3). There are three final  $p\bar{p}$  states allowed by  $P$  and  $C$  conservation in the  $\gamma p\bar{p}$  channel. These are listed in tables I and II and denoted by  $^{2S+1}L_J$  or  $^{2I+1,2S+1}L_J$ ,  $S, L, J$  being the spin, angular momentum, total momentum of the pair and  $I$  denotes the isospin. Radiative decay does not conserve isospin but already in Ref. [3] it was realized that  $I = 0$  is the state which leads to the enhancement. From potential descriptions of  $N\bar{N}$  interactions based on the  $G$ -parity rule it is known that the pion exchange potential is very strong in this state being capable to form bound

\* Contribution to EXA2014 Vienna to appear in a special edition of Hyperfine Interactions.

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states. On the other hand the annihilation and short range interactions act repulsively, thus quasi-bound states are not guaranteed. In particular the Paris potential generates a 52 MeV broad quasi-bound state at 4.8 MeV below threshold [4] but the Bonn-Jülich potential does not generate bound state in this wave [5]. Both can describe the threshold enhancement [5, 6].

The radiative process itself is puzzling as the decay rate is comparable to the mesonic decay rates. On the other hand the conventional coupling constants  $\alpha/g_{NN,meson}^2$  are  $\sim 10^{-3}$  and a strong enhancement mechanism has to exist. In section II this question is discussed jointly with the origin of the threshold enhancement. There are other indications

TABLE II: Decay modes and the  $p\bar{p}$  states allowed in the  $J/\psi \rightarrow \text{boson } p\bar{p}$  decays.

decay mode	branching	$p\bar{p}$ states allowed
$\gamma p\bar{p}$	$3.8(\pm 1.0) \cdot 10^{-4}$ [7]	$^1S_0, ^3P_1, ^3P_0$
$\omega p\bar{p}$	$1.1(\pm 0.15) \cdot 10^{-3}$ [8]	$^{11}S_0, ^{13}P_1, ^{13}P_0$
$\pi^0 p\bar{p}$	$1.19(\pm 0.08) \cdot 10^{-3}$ [7]	$^{33}S_1, ^{31}P_1$
$p\bar{p}$	$2.12(\pm 0.1) \cdot 10^{-3}$ [7]	$^{13}S_1$

of  $N\bar{p}$  structures existing below threshold coming from antiprotonic atoms. These are discussed in section III. In section IV we list possible experimental researches of the baryonia which could be performed in a near future.

## II. FINAL STATE INTERACTIONS IN $J/\psi$ DECAYS

We have attempted calculations of the radiative and mesonic decay rates presented in table II, assuming that mesons are emitted in the final states of the decay when the baryons have been formed. With conventional meson-nucleon coupling constants this model reproduces branching ratios of *meson*  $p\bar{p}$  channels relative to the basic  $p\bar{p}$  channel [9]. It offers also a consistent description of the spectra in cases of  $\pi^0, \omega$  mesons at the expense of one free parameter, the  $N\bar{N}$  formation radius  $R = 0.28 \text{ fm}$ . However, this model fails in the description of radiative decays in two ways: first the branching ratio is only about 1/3 of the experimental one, and second the threshold enhancement is not reproduced. The transition to  $^1S_0$  state is a magnetic one and it turns out that in the intermediate stage of such decay one has both  $p\bar{p}$  and  $n\bar{n}$  as intermediate states. Since the magnetic moments of  $p$  and  $n$  have opposite sign the effect of final state enhancement cancels strongly. At the same time such a model indicates that final state interactions increase the overall decay rate by an order of magnitude in the  $I = 1$  states.

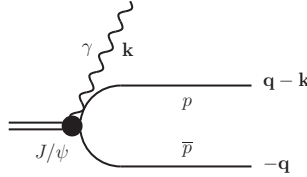


FIG. 1: The photon is emitted either from  $J/\psi$  or during the hadronisation stage of the process and the final baryons are formed in the  $S$  wave

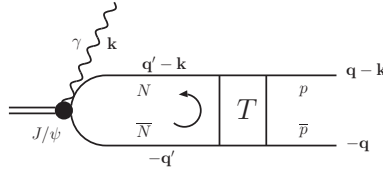


FIG. 2: The final state interaction is described by half-off shell  $T$  matrix generated by the Paris potential

In this note we report an extension of the FSI calculations of Ref. [6] which is now used to cover the whole photon spectrum. The basic assumption of this approach (also that in Ref. [5]) is that the photon is emitted before the baryons are formed. The two related processes are in the diagrams of Figs. 1 and 2 and the FSI is calculated in terms of half-off shell  $T$  matrix generated by the Paris potential [4] plotted in figure 4. This approach allows to calculate the spectrum but not the absolute decay rate. One free parameter, the radius  $R$  ( $=0.28 \text{ fm}$ ) of a Gaussian source

function is used to describe the creation of a  $\gamma p\bar{p}$  state (see figure 1). However, in order to reproduce in a better way both maxima in figure 3 (the  $X(1859)$  and  $X(2170)$  in BES terminology), it turns out profitable to assume the radius to be weakly dependent on the photon energy. It was found to change from 0.28 fm at maximal  $k \sim 1.2$  GeV to 0.39 fm at  $k = 0$ .

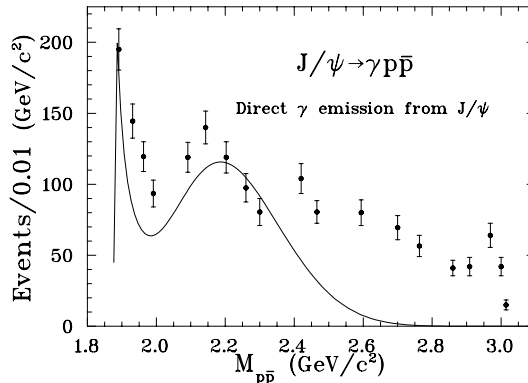


FIG. 3: The  $p\bar{p}$  invariant mass spectrum obtained under the assumption that the photon is emitted before the baryons are formed. The missing strength at large  $p\bar{p}$  invariant mass,  $M_{p\bar{p}}$ , comes from the photon radiated by final hadrons [9]

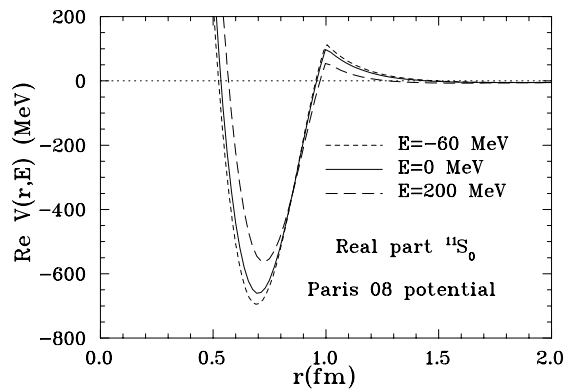


FIG. 4: The Paris  $N\bar{N}$  real potential in the  $^1S_0$  wave. It generates a 50 MeV broad quasi-bound state at  $\sim 5$  MeV binding. The well and barrier structure generate the shape resonance visible in the spectrum in figure 3 at 2170 MeV

Inspection of figure 3 shows that both states may be reproduced by the  $N\bar{N}$  potential related at large distances via G-parity transformation to the  $NN$  interactions. However, the proper description of both peaks involves distant extrapolation of the  $T_{N\bar{N}}$  matrices off energy shell, which corresponds to very short range interactions. This figure shows also that a sizable portion of the spectrum is missing and this part comes from photon emissions by final  $N\bar{N}$  baryons and exchange currents [9].

As already discussed the threshold enhancement indicates a "nearby singularity" that might describe an analogue of the bound state or the virtual state known from the physics of two nucleons. To discern these possibilities one has to test directly the sub-threshold region.

### III. STUDIES OF THE $N\bar{N}$ SUB-THRESHOLD REGION

One way to look below the threshold is the detection of  $N\bar{N}$  decay products. The specific decay mode

$$J/\psi \rightarrow \gamma \pi^+ \pi^- \eta' \quad (2)$$

has been studied by the BES collaboration [10]. This reaction is attributed by BES to an intermediate  $p\bar{p}$  configuration in the  $J^{PC}(p\bar{p}) = 0^{-+}$  state that is the  $^1S_0$  wave. A peak in the invariant mass of the mesons was observed and was interpreted as a new baryon state and named  $X(1835)$ .

Under the assumption that all mesons are produced in relative  $S$ -waves the reaction (2), if attributed to an intermediate  $p\bar{p}$ , is even more restrictive than the reaction (1). It allows only one intermediate state, the  $p\bar{p} \ ^1S_0$ , which coincides with the previous findings. The intermediate state of  $p\bar{p}$  in reaction (2) is possible but not warranted. In Ref. [11] a more consistent interpretation is obtained with the dominance of the  $^1S_0$  state which is a mixture of  $p\bar{p}$  and  $n\bar{n}$  pairs. It has been argued that the peak is due to an interference of a quasi-bound, isospin 0,  $N\bar{N}$  state with a background amplitude. A typical interference pattern obtained in this way is plotted in figure 5. It is fairly close to the data. The same quasi-bound state was found in Ref. [6] to be responsible for the threshold enhancement in reaction (1). In this sense Paris potential unifies the two effects and attributes it to single quasi-bound state with an energy dependent width.

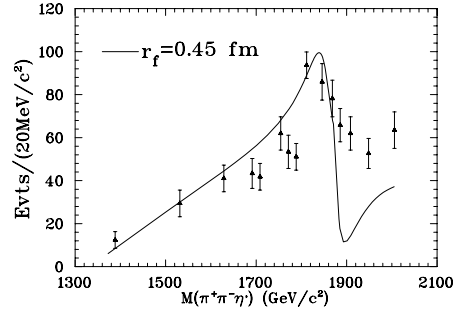


FIG. 5: The spectral function  $X_S$  representing the  $X(1835)$  shape. The parameter of the annihilation range is  $r_f = 0.45 \text{ fm}$ . This  $S$ -wave contribution has been normalized to reproduce the data close to the  $X(1835)$  peak. The experimental points are from Ref. [10], calculation from Ref. [11].

Testing the subthreshold amplitudes may be also realized in few body systems in particular in light antiprotonic atoms or at extreme nuclear peripheries. In these conditions nucleons are bound and the effective subthreshold energies are composed of binding energies and recoil of the  $N\bar{p}$  pair with respect to the rest of the system. For valence nucleons the  $E_{\text{binding}} + E_{\text{recoil}}$  may reach down to  $-40 \text{ MeV}$  below threshold. Let us indicate an atomic experiment that discovered an interesting anomaly. Table III shows the ratios of antiproton capture rates on neutrons and protons  $C(n\bar{p})/C(p\bar{p})$  bound to nuclear peripheries. These reflect the ratios of neutron and proton densities. The second and third columns indicate such ratios extracted from widths of two antiprotonic atomic levels the "lower" and the "upper" one. These widths are determined at nuclear densities  $\sim 10\%$  and  $\sim 5\%$  of the central density  $\rho_0$ . The last column is obtained with radiochemical studies of final nuclei with one neutron or one proton removed in the annihilation reaction [12]. The latter process is localized at densities  $\rho \sim 10^{-3}\rho_0$ . In standard nuclei shown in the upper part of the table the ratios  $N(n\bar{p})/N(p\bar{p}) \sim \rho_n/\rho_p$  increase at nuclear peripheries. However, in some nuclei characterized by small proton binding, indicated in the lower part of the table, and typical ( $\sim 8 \text{ MeV}$ ) neutron binding the ratio  $N(n\bar{p})/N(p\bar{p})$  suddenly drops at extreme nuclear peripheries. That effect cannot be explained by the nuclear structure alone and we attribute it to the existence of a narrow bound state in the  $N\bar{N}$  system. Such a narrow state is in fact predicted by the Paris potential in the  $^{33}P_1$  wave, see table IV.

TABLE III: Ratios of  $N(n\bar{p})$  and  $N(p\bar{p})$  capture rates from atomic states. The last column shows experimental numbers from radiochemical experiments. Other columns (see text) give ratios calculated with optical potential and plausible nuclear densities based on experimental results from Ref. [12].

atom	lower	upper	radiochemistry
$^{96}\text{Zr}$	0.95(9)	1.53(29)	2.6(3)
$^{124}\text{Sn}$	1.79(10)	2.44(39)	5.0(6)
$^{106}\text{Cd}$	1.64(80)	2.10(80)	0.5(1)
$^{112}\text{Sn}$	1.90(13)	2.43(49)	0.79(14)

TABLE IV: Binding energies in MeV of the close to threshold quasi-bound states in the Paris potential [4]

$^{2T+1} \ ^{2S+1} L_J$	$E - i\Gamma/2$
$^{11}S_0$	-4.8-i26
$^{33}P_1$	-4.5-i9.0

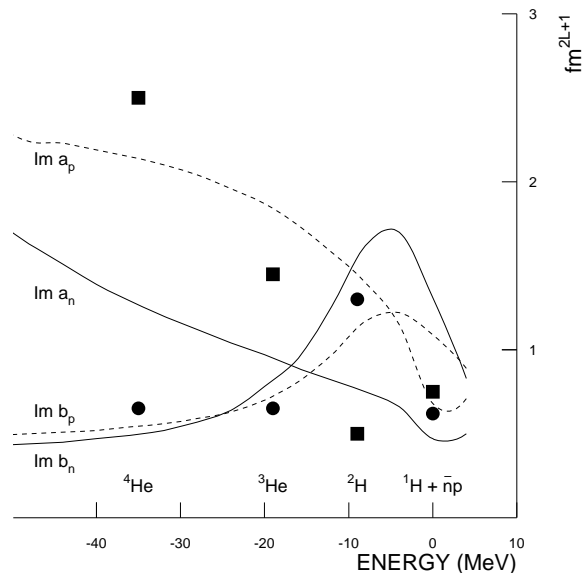


FIG. 6: The absorptive parts of spin-isospin averaged  $N\bar{p}$  scattering amplitudes extracted from the atomic level widths in antiprotonic H,  $^2\text{H}$ ,  $^3\text{He}$  and  $^4\text{He}$  [13, 14]. Squares:  $S$  waves and circles:  $P$  waves. The bottom scale indicates the energy below threshold. The curves, calculated with the Paris potential, give the amplitudes separately:  $a_{n(p)}$  denote the  $n\bar{p}$  or  $p\bar{p}$   $S$ -wave amplitudes. Similarly  $b_{n(p)}$ ,  $b_{p(p)}$  are the corresponding  $P$ -wave amplitudes. The strong increase of absorption in the  $\bar{p}p$   $S$  wave is attributed mainly to the  $^{11}S_0$  state.

A similar effect is indicated by studies of experimental absorption lengths in light antiprotonic atoms [13, 14]. From the lower and upper atomic level widths one can extract average  $S$  wave absorption length  $\text{Im } a$  and  $P$  wave absorption volumes  $\text{Im } b$ . The results shown in figure 6 indicate increase of the absorption in the  $S$  wave down below the threshold. This result is consistent with the presence of the  $X(1835)$  state. The absorption volume extracted from antiprotonic deuterium indicates some enhancement possibly related to radiochemical anomalies observed in nuclei with loosely bound protons and interpreted in terms of Paris potential as the  $P$  wave bound state.

#### IV. NEW ERA

Following indications from antiprotonic atoms and from BES experiments the baryonia should be searched in the region of 0-60 MeV below the  $N\bar{N}$  threshold. With the new  $\bar{p}$  beams expected to operate in J-PARC and FAIR it would be advisable to repeat two old experiments possibly at different energies, possibly with polarized particles:

- Search for narrow signals in the  $\gamma$ -spectrum from  $p\bar{p}$  annihilation was performed at rest [1]. The signals (in the region that we expect them now to exist) were covered by heavy background due to  $\pi^0$  decays and  $\pi^-p \rightarrow \gamma n$ . It would be better to perform this experiment with higher energy antiprotons (a few hundred MeV/c) antiprotons which could shift the expected signal away from the heavy background region.

- The  $\bar{p}d \rightarrow nX$  experiment [2] was performed at 1.3 GeV/c. This gives rather small chance of  $p\bar{p}$  coupling in the statistically insignificant  $^{11}S_0$  wave. Lower energies and polarized (one or two particles) would reduce the background.

New instructive experiments that possibly could be performed at FLAIR are:

- Fine structure splitting in light antiprotonic atoms  $^1\text{H}$ ,  $^2\text{H}$ ,  $^3\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$  would allow to trace energy dependence of the selected  $\bar{p}N$  amplitudes in the subthreshold region down to  $\sim -40$  MeV.

- Studies of mesons emitted from annihilations of  $\bar{p}$  at nuclear peripheries. In particular nuclei with closed shells with one loosely bound valence nucleon could be profitable. In the latter case the baryonium signal would be separated from a complicated background due to other annihilation channels.

This work has been partially supported by a grant from the French-Polish exchange program COPIN/CNRS- IN2P3, collaboration 05-115. SW was also supported by Narodowe Centrum Nauki grant 2011/03/B/ST2/00270.

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